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ON THE POSSIBILITY OF SIMULATING
METEOROID IMPACT BY THE USE OF LASERS

by

William J. Rae and A. Hertzberg

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Buffalo, New York 14221

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TOPICAL REPORT

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FOREWORD

This report evolved from theoretical studies of hypervelocity impact sponsored by the Lewis Research Center of the National Aeronautics and Space Administration. Publication of the simulation concept described herein has been supported by this contract because of its potential interest.

ABSTRACT

This report discusses the possibility of studying the problem of meteoroid damage by using a laser to simulate the conditions of high-speed impact. The characteristics of the light output from a laser allow a strongly focused pulse of energy to impinge on the target surface. The principal content of the report is a critical examination of the extent to which such irradiation simulates the conditions of impact by a solid projectile.

The present state of knowledge concerning meteoroid-impact damage is briefly reviewed, in order to illustrate the regimes where new information is needed. With this as a background, the capabilities of a laser are examined. It is concluded that such a simulation offers sufficient potential to justify exploratory experiments. Suggestions are made for certain initial experiments, and some of the problems likely to be encountered are pointed out.

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I. INTRODUCTION

The prediction of the damage likely to result from a given meteoroid impact poses a number of problems which are not readily amenable to available experimental or theoretical approaches. Basically, the difficulty can be traced to the extreme speed (10-70 km/sec) of the meteoroids. The lack of a reliable penetration law at such speeds has prompted considerable theoretical effort, and has called forth some very ingenious developments in ballistic-range technology. While recent results[1] at 11 km/sec indicate the steady progress being made, nevertheless it appears that any major advance in speed still lies some years in the future.

This report discusses the possibility of simulating impact in the hypervelocity regime by irradiating the target surface with a pulse of intense electromagnetic energy from a Q-spoiled laser. The capability of such a device for producing material damage has been apparent for some time,[2] but there has always been a question whether such an irradiation simulates the conditions of impact by a solid particle. However, some recent experimental and theoretical studies of hypervelocity impact have produced results which indicate an affirmative answer. In particular, it has been noted that, at high impact speed, the energy imparted by the projectile plays the dominant role in determining the disturbance produced, with the momentum carried by the projectile playing a minor role. Thus, any method of energy deposition in a target may be considered for simulating the conditions of hypervelocity impact, irrespective of whether or not the momentum of the projectile is duplicated.

For the simulation to succeed, the energy source must meet certain specifications related to the total energy delivered, the deposition time, and the size of the spot irradiated. It was pointed out in the appendix of Ref. 3 that the laser could meet these specifications. The three sections below present a more detailed critique of the simulation possibilities.

The first section (Section II) is a brief review of the present state of knowledge of the theoretical and experimental aspects of the meteoroid damage problem. With these as a background, Section III presents the basis of the simulation. The fourth section describes the suggested experiment, indicating crucial measurements that are necessary to establish the limits of validity of the simulation.

No extensive discussions of laser principles are given in this report. Background material describing their theory and operation may be found, for example, in Refs. 4 and 5.

II. THE METEOROID IMPACT PROBLEM

This section consists of a brief review of present knowledge of the damage produced in a dense medium when struck by a fast-moving particle. Both theoretical and experimental evidence are examined.

Status of Theory

The dominant characteristic of the phenomena that are brought into play during hypervelocity impact is the large magnitude of the pressures that are generated. Because these pressures exceed the material strength by many factors of ten, it is possible to treat the deformation as the flow of a compressible, inviscid fluid. Sophisticated computer programs have been developed[6,7] which permit a numerical treatment of the inviscid equations of motion; parallel developments, based on blast-wave theory[3,8-10] have produced useful approximations.

An indication of the success of hydrodynamic theory in this regime is its prediction of the history of shock propagation through the targets. These shocks have been observed to be very nearly hemispherical in shape in transparent targets,[11,12] in wax,[13,14] and in the computer solutions as well.[6,7] Thus, a prediction of the shock radius versus time after impact can serve as a check on the inviscid theory. Unfortunately, no direct comparison between computer-predicted shock trajectories and experiment has ever been made. However, the pertinent scaling parameters required to put all these data on a common footing are known from blast-wave theory.[3] Provided the time scale for shock propagation is large compared to the time during which the projectile is destroyed, all shock histories in a given target are correlated when the shock radius R_s and time after impact, t , are divided,

respectively, by $R_0 = \left(E / 2\pi \rho_0 c^2 \right)^{1/3}$ and R_0/c , where E is the kinetic energy of the projectile, ρ_0 the normal target density, and c the stress-wave velocity of the target. Figure 1 shows the correlation of the rather sparse data that have been published to date. Part of the scatter in the data is due to differences in the target materials, which vary, for the cases shown, from tuff (a porous rock) to iron. The correlation is quite good, considering the wide range of materials and of impact speeds, and provides evidence for the correctness of the inviscid theory in describing the high-pressure portions of the flow.

On the other hand, such a theory contains no mechanism by which the material can be brought to rest. To make an unequivocal determination of the crater size, it is necessary to reinstate the effect of material strength. Unfortunately, this is an extremely difficult task, both analytically and numerically. Several recent studies have been made, [15-18] but the problem of predicting crater size remains unresolved. Not the least of the problems faced in such analyses is the question of what model to use. The field of viscoelasticity admits a variety of models, and it is not always clear which of these is best to use, nor whether the pertinent material constants can be specified.

Because the inviscid theories do not, of themselves, predict a final crater size, the proponents of such theories must adopt some auxiliary criterion for its determination. Different criteria have been used by various authors, notably by Walsh and Tillotson[6] and by Bjork.[7] Thus it is not surprising to find that the two most advanced computer solutions are interpreted by their authors to give widely different predictions of crater size. Bjork[7]

feels that crater radius will grow with the 1/3 power of impact speed, while Walsh and Tillotson[6] favor the 0.62 power.

In summary, it can be said that the fluid-mechanical models do correctly determine shock trajectories, which can be correlated for various cases. However, there is presently no agreement as to the scaling law for crater size, and no generally accepted theoretical means of predicting it.

Status of Experiment

The uncertainties that are present on the theoretical side have their counterparts in experiment.[19] A wide variety of scaling laws and empirical correlations can find some experimental data over the limited range of impact speed to support them, but there are always a significant number of unexplained exceptions. It is clear that a large number of factors are present - - the shock-wave properties and energy-absorbing capabilities during the inviscid phase, the temperature, hardness, dynamic strength, melting and resolidification during the later stages, to mention only a few.

Since the data presently available do not extend to a large enough impact speed, these various effects cannot be sorted out. To remedy the situation, some very ingenious techniques have been introduced in recent years for extending the capability of ballistic ranges. As a result of these efforts, velocities slightly in excess of 10 km/sec have been achieved. Performance of this sort is especially admirable, in that it begins to approach some of the upper limits of ballistic-range operation. The nature of this limiting condition, as well as fruitful avenues for further development, have been illustrated by Charters[20] and by Curtis and Gehring,[21] by considering the simple mechanics of accelerating a mass point. They point out that all accelerators

are limited by the fact that the length of launch tube L required to achieve a given muzzle velocity V at constant acceleration a (i. e., with constant pressure exerted on the base of the projectile) varies as the square of the desired velocity

$$L = \frac{1}{2} \frac{V^2}{a} \qquad (1)$$

The maximum pressures that can be applied without serious deformation correspond to accelerations on the order of 10^6 gravities. Thus, according to Fig. 2, the launcher must be at least 45 meters long to achieve 30 km/sec. Unfortunately, it is not presently possible to maintain the base pressure (and hence the acceleration) constant over such a long distance, and thus the length of an actual launcher must be several times the size indicated in Fig. 2. The accelerated-reservoir technique[20] has demonstrated its ability to improve the constancy of base pressure, but a relatively long period of development appears to be required before facilities of that type will be able to launch well-defined projectiles at speeds in the meteoroid range.

It is possible to achieve higher accelerations if an attendant compromise in projectile definition can be tolerated. Typical of the problems encountered by such an approach are those of the exploding-foil apparatus, for which impact speeds as high as 20 km/sec have been reported.[22] While this device appears to hold promise, nonetheless there remain unanswered questions about particle definition, in addition to other anomalies (for lead targets) which appear to be unique to the exploding-foil results.

The status of experiment can be summarized by stating that data do not extend sufficiently far into the speed range beyond 10 km/sec to resolve

present uncertainties in scaling laws for crater size. The development period that must precede the achievement of such velocities in ballistic ranges raises the question whether a laser might be capable of producing the desired information more quickly and more economically. In the remaining sections of this report, the potentialities and the limitations of using a Q-spoiled laser for this purpose are examined, and it is concluded that the technique holds sufficient promise to warrant exploratory investigations.

III. BASIS OF THE SIMULATION

This section presents the experimental and theoretical results on which the simulation is based, and describes the minimum performance capabilities the laser system must possess.

Insensitivity to Projectile Momentum

It has been observed[1] that a target struck by a hypervelocity projectile acquires momentum many times that of the projectile, implying that the material ejected from the target must also carry several times the projectile momentum, in the direction opposite to that acquired by the target. Thus, the disturbance generated by hypervelocity impact consists essentially of two large parcels of momenta, oppositely directed. The small difference of these two large quantities represents the projectile momentum. Because the difference is small, it may be expected that a proper simulation of hypervelocity impact could be achieved by any other process which generates two large and oppositely directed parcels of momentum, whose vector difference is small. This is precisely the situation created by the irradiation of a target surface by an intense laser burst.

The minor role played by the projectile momentum is also apparent from theoretical studies of hypervelocity impact. For example, the solutions of Walsh and Tillotson[6] reveal that the flow patterns resulting from two impacts having the same energy, but different momenta, are approximately the same at late time. In addition, the correlation of shock trajectories, given above, utilized only the energy of the projectile, ignoring its momentum.

Requirements for Shock-Wave Generation

While it may be granted that momentum duplication is unimportant, there remains a serious requirement that the mode of energy release must drive a strong shock wave into the target. Particularly for the case of energy deposition in electromagnetic form, it is necessary to determine the intensity level at which this requirement is met.

As the rate of energy input to a solid is increased, energy absorption by the linear process of heat conduction must eventually be insufficient to cope with the supply. An estimate of the level at which this occurs can be inferred from the classical linear-theory results themselves.[23] Detailed calculations of the temperature rise in metals have been presented, for example, by Ready.[24] His results show that for incident power densities greater than 10^9 watts/cm^2, the surface temperature of a metal typically exceeds the boiling point in one nanosecond. Since even a "short-pulse" laser has a discharge time the order of ten nanoseconds, it is clear that a linear theory is inappropriate at power densities greater than 10^9 watts/cm^2. In this regime, some nonlinear process presumably becomes important.

It is a fundamental hypothesis of the suggested simulation that, at sufficiently high rates of energy input, shock waves will be generated as the means of energy absorption. The evidence for such a mechanism is drawn from the magnitude of the pressure pulse that is applied to a target surface during intense irradiation. When material is being evaporated from the surface at a rapid rate, a large recoil pressure is generated in the target.

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In addition, the radiation pressure itself becomes appreciable at high power densities. Askaryan and Moroz[25] have recently presented an order-of-magnitude estimate of these effects. They conclude that the recoil pressure will be on the order of 10^4 to 10^5 times as great as the radiation pressure. The resulting pressures, listed in Table I below, indicate that shock-wave generation must be expected* whenever the power density exceeds 10^{10} watts/cm^2.

TABLE I

Pressures Generated During Laser Irradiation

| Power Density w/cm^2	Radiation Pressure megabars	Recoil Pressure megabars
3×10^9	10^{-6}	$10^{-2} - 10^{-1}$
3×10^{12}	10^{-3}	$10^1 - 10^2$
3×10^{15}	1.0	$10^4 - 10^5$

It is interesting to note that the predicted onset of shock-wave generation (at approximately 10^{10} watts/cm^2) is consistent with the level at which the linear heat-conduction mechanism breaks down (around 10^8 to 10^9 watts/cm^2).

The maximum power density attainable with contemporary Q-spoiled lasers lies well above 10^9 watts/cm^2. The maximum value attainable continues to rise at a rapid rate; one recent survey[27] indicated 10^{15} watts/cm^2

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* The possibility of shock-wave generation by a laser is also mentioned in a recent paper by Missio.[26]

as a representative upper limit for existing devices. Typical of the rapid growth in laser capability is the development of the oscillator-amplifier type, recently made available by several firms.

It is possible to derive the same lower limit for the threshold of shock generation by an entirely different consideration. This lower limit may be established by assuming that the laser output has generated a shock wave, and then inquiring what level of intensity is required to maintain it. Such a process consists essentially of matching the magnitude of the Poynting vector of the electromagnetic radiation to the shock strength. To understand the matching, it is necessary to think of a shock wave as an agent which delivers a certain power per unit area to the medium through which it travels.[*] Consider a plane shock advancing at speed u_s into a medium of undisturbed density ρ_0

$$
\begin{array}{c|cc}
\rho_1, \ p_1, \ e_1 & & \rho_0, \ p_0, \ e_0 \\
u_1 \neq 0 & \xrightarrow{\ u_s\ } & u_0 = 0
\end{array}
$$
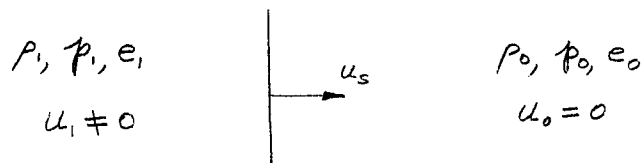
In unit time, the shock processes an amount of mass given by $\rho_0 u_s$, per unit area. One can derive from the shock conservation laws that the internal energy delivered per unit mass is given by

$$
e_1 - e_0 = \frac{p_1}{2\rho_0}\left(1 - \frac{\rho_0}{\rho_1}\right) \tag{2}
$$

where the pressure ahead of the shock, p_0, is neglected in comparison to p_1. The shock also imparts kinetic energy, which to the same degree

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[*] The concept of the power-density rating of a shock wave is mentioned by Rice, McQueen, and Walsh (see p. 9 of Ref. 28).

of accuracy is equal to $e_1 - e_0$. Thus the rate of energy acquisition by the material behind the shock, per unit time and area, is[*]

$$\text{power/area} = 2 \rho_0 u_s \frac{p_1}{2 \rho_0} \left(1 - \frac{\rho_0}{\rho_1} \right) = p_1 u_1 \tag{3}$$

The strength of any shock wave may therefore be characterized by the amount of power per unit area which it delivers to the medium through which it travels. The known shock-wave results[28,29] for iron are interpreted in this light in Fig. 3, where it is seen that weak shock waves ($p_1/p_0 \approx$ 1.3) impart about 10^{10} watts/cm^2, while extremely strong shocks ($p_1/p_0 \approx$ 3) transfer to the medium some 10^{13} watts/cm^2. These orders of magnitude indicate that, to drive a significant shock into a metallic target, a power density of at least 10^{10} watts/cm^2 is required, in accord with the conclusions reached above.

The results shown in Fig. 3 are typical of many solids, as can be seen by examining the power-density rating of a solid whose Hugoniot displays a linear shock speed-particle speed relation:

$$u_s = C + S u_1 \tag{4}$$

where C is approximately the stress wave speed, and S is a constant on the order of one to three. A large number of materials obey such a relation, and values of the constants C and S can be found, for example, in Ref. 28. A tabulation for a number of typical solids is given in Table II. For such a material, use of the Rankine-Hugoniot equations leads to the following relation between power density and the mass-density

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[*] The factor two appearing in this equation was omitted in Refs. 3 and 8. Thus the power densities listed in the present report are twice as large, at a given shock strength, as those of the previous papers.

ratio across the shock:

$$\frac{\text{power/area}}{\rho_0 c^3} = \frac{\frac{\rho_1}{\rho_0}\left(\frac{\rho_1}{\rho_0} - 1\right)^2}{\left[s - (s-1)\frac{\rho_1}{\rho_0}\right]^3} \tag{5}$$

The quantity $\rho_0 c^3$ is typically on the order of 10^{10} watts/cm^2, while

the right-hand side of this expression varies from around 10^{-2} up to 10^4

in the regime where Eq. (4) is valid. Thus the orders of magnitude cited

above may be considered typical of most solids.

From the point of view of meteoroid-impact simulation, these power-

density ratings provide an indication of the equivalent impact velocity that

can be simulated. Figure 4 gives the power-density ratings of the shock

waves that are generated by iron-on-iron impact.[*] If all of the laser energy

goes into driving the shock, then power densities like 10^{13} watts/cm^2 could

simulate impact at speeds on the order of 40 km/sec.

Independent Variation of Energy and Momentum

Because of the current controversy between "energy scaling" and

"momentum scaling" of crater volume in hypervelocity impact, it is impor-

tant that any technique for studying the problem be capable of independently

varying the energy and momentum imparted to the target. Simulation by a

laser does provide such a capability. The reason for this can be seen in the

results of Askaryan and Moroz.[25] The momentum acquired by the target

during irradiation with a given amount of energy consists of the momentum

due to radiation pressure, plus the recoil momentum. The first of these is

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[*] Methods for calculating the strengths of the shock waves generated at the
impact point are given, for instance, in Ref. 8, pp. 17-18.

directly proportional to the total energy, but the second depends on other factors, such as the power density. Thus it should be possible to achieve an independent variation of energy and momentum by focussing a given amount of energy to a succession of different spot sizes.

Sensitivity to Pulse Shape

The objective of the technique described here is to simulate the effects, such as the crater size, produced by impact with a meteoroid. To do so, it is not necessary to reproduce exactly the same surface pressure pulse as experienced in a particle impact. The information desired relates to the configuration in which the material ultimately comes to rest; this takes shape on a time scale that is long compared with the period of excitation at the surface. By that time, the material has essentially lost all memory of the fine structure of its initiation process. This fact has long been recognized in hypervelocity experiments, where the craters produced by a cube or a sphere are the same. It also constitutes the justification for the use of a right-circular cylinder as the projectile in the computer solutions, and for the use of an instantaneous point-release of energy in the blast-wave approach.

Such insensitivity to the detailed structure of the excitation forms part of the basis for the simulation suggested here. It must be recognized that irradiation by a laser will not generate precisely the same pressure pulse as that produced in particle impact, due to the presence of such factors as heating by absorption, and interaction of emitted vapor with the beam. For the purpose of studying meteoroid-impact damage, however, it is only neces-sary that the pulse be short compared to the time required to produce the damage, and that the pulse be capable of generating a shock wave.

Effects Noted at Lower Power Densities

An intense flux of electromagnetic radiation can be delivered by a variety of devices. The main distinctive feature of the laser is that its beam, being coherent, can be focused much more sharply, so as to generate a more intense flux. It is interesting, however, to note some of the effects that have been produced by various devices at power-density levels below those being considered here.

By focusing the emission from a flash lamp, Nelson and his associates[30] have irradiated various materials with as much as 10^4 watts/cm^2. Even at this modest level, temperatures of 5000°K are quickly produced in thin samples. The same technique has recently been employed up to 5×10^4 watts/cm^2 by Good,[31] who observed crazing and cracking of a glass target, in spite of its relative transparency. Electron beams, capable of producing 10^9 watts/cm^2, have been employed by Heil and Vogel[32] to produce severe damage to metals. Another series of experiments at power-density levels on the order of 10^9 watts/cm^2 has recently been reported by Lichtman and Ready;[33] these authors were able to explain their observations on the basis of a heat-conduction mechanism.

An interesting experiment, from the present point of view, has been reported recently by Ready,[34] who used a laser to irradiate a carbon block with a power density of approximately 10^{10} watts/cm^2. A glowing plume of vaporized material was ejected from the target surface, shortly after termination of the laser pulse. It appears that most of the incident energy was initially invested in nonequilibrium excitation, which was subsequently transferred to translational energy of the carbon atoms during the relaxation toward equilibrium.

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Finally, some recent papers on stress-wave generation by absorption of electromagnetic radiation should be noted.[35-38] The earliest of these is the work of Michaels,[35] who detected the generation of stress waves when the radiant energy from an exploding wire was focused on one end of an aluminum rod. This experiment (performed at several hundred watts/cm^2) together with an analysis of the stress produced by thermal expansion, led Michaels to conclude that a power density on the order of 10^8 watts/cm^2 would cause damage in aluminum. Subsequent to this work, there appeared a series of papers by White[36-38] reporting the generation of stress waves by microwaves, electron beams, and a laser. One of the important contributions of White's work was to point out that the stress amplitude is considerably greater than the radiation pressure, even at the low end of the power-density spectrum. White also called attention to the generation of very high-frequency acoustic waves by pulsed electromagnetic energy, which had been anticipated by Askaryan and Moroz.[25]

White's measurements have shown a linear dependence between the incident power density and the amplitude of the stress wave produced. Such a relation is predicted by uncoupled thermoelastic theory. It is interesting to compare this observation with the weak-wave limit of the analysis presented above, in which the power-density ratings of shock waves were calculated. For a material which has a linear shock speed-particle speed relation, the expression linking the power density to the pressure generated behind the shock is (this pressure may be considered the nonlinear counterpart of the stress amplitude)

$$\frac{\text{power}/\text{area}}{\rho_0 c^3} = \frac{p_1}{\rho_0 c^2} \frac{\sqrt{1 + 4S\, p_1/\rho_0 c^2} - 1}{2S} \tag{6}$$

In the weak-wave limit, this yields a square-root dependence

$$\frac{p_1}{\rho_0 c^2} \approx \left\{ \frac{\text{power}/\text{area}}{\rho_0 c^3} \right\}^{1/2} \tag{7}$$

in contrast to the linear dependence that is observed. The reason for

the discrepancy is that the strong-shock mechanism is not the proper one

in the regime of White's measurements. The simple energy conservation

that led to the power-density rating of a strong shock is inappropriate in

the range where essentially all the input goes into heating the solid.[*]

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[*] The beginning of the transition from the purely thermal regime to the
regime where the strain energy imparted by the wave is appreciable could
be investigated by a rigorous application of coupled thermoelastic theory
(Refs. 16 and 39 for example) but this point is not pursued in the present
report.

IV. EXPERIMENTAL APPROACH

This section describes the suggested experiment, and calls attention to some of the problems that are likely to be encountered.

Scale of the Experiment

The range of energies encountered in the meteoroid impact problem is shown in Fig. 5. As noted previously, the impact velocities of concern extend from 10 to 70 km/sec. The range of masses most likely to cause damage depends on the nature and duration of the space mission. For long-duration protection of a space radiator, for example, particles from 10^{-4} to 10^{-1} gm must be considered.[41] A mission of shorter duration, which is less apt to encounter the infrequent large particles, requires consideration only of smaller ones. The duration of impact, estimated as the meteoroid diameter divided by its speed, is on the order of 10^{-7} to 10^{-8} seconds (for a density on the order of 1.0 gm/cm^3).

Ballistic-range measurements are generally restricted to the region above 10^{-2} gm, and to velocities less than 10 km/sec. Typical present-day lasers, operating in the Q-spoiled mode, are capable of delivering approximately 1 to 10 joules, in approximately 10^{-8} to 10^{-7} seconds. Thus, the regime accessible to the laser lies well within the boundaries of the meteoroid environment.

In order to relate the damage produced by the laser to an equivalent particle impact, some determination of the shock trajectory within the target will be needed. Measurements of such gross quantities as crater size or target momentum are not enough. From this viewpoint the most important feature to be noted is that the laser energy is on the order of

several joules. Taken in conjunction with the cube-root energy scaling illustrated in Fig. 1, the implication is that the time and distance scales for the experiments will be of the same order as those of the actual meteoroid environment, that is, they will lie in the submicrosecond, subcentimeter range. To make measurements on such a scale will require considerable care.

Details of Experiments in Lucite

Much of our present understanding of the mechanism of hypervelocity impact has come from observations in transparent targets.[11] It would be well to use such materials in the initial experiments with the laser, in order to establish its connection with ballistic-range results, and to provide a convenient setting for the development of experimental technique. Lucite offers several advantages in this regard. It has an absorption band[*] in the infrared,[41] which includes the wavelengths of many contemporary lasers. In addition, shock waves in this material can easily be photographed by available techniques.[11] Thus, an interesting experiment would be to irradiate a block of Lucite, taking a short-duration photograph from the side at a short time after the laser pulse. A series of such photographs taken with various time delays after the laser pulse would reveal details of the shock propagation. These results could be used in conjunction with the

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[*] The absorption is approximately 50% for a 1 cm thick specimen, at a wavelength of about 3.3μ. These results apply, of course, only for a radiation flux far below that contemplated here, and sufficiently low that even the temperature rise due to absorption may be neglected. It is difficult to predict what the absorption spectrum will be at large power densities, but the existence of an absorption band at normal conditions suggests that Lucite will be strongly absorbing under the conditions of the experiment.

correlation predicted by blast-wave theory to infer from the observed trajectory the amount of energy absorbed.

Details of the shock trajectory anticipated in a Lucite target are shown in Fig. 6, for several values of the energy absorbed. The constant-energy curves are taken from the quasi-steady theory of Ref. 3, and are based on the approximation of an instantaneous point-release of energy. Such an approximation does not apply at early time; during this period, the shock is assumed to travel at a constant speed, dependent only on the power-density level. Points on the trajectory are shown at which the shock speed is 10 times and 1.2 times the stress-wave speed. The slower speed may be taken as representing termination of the strong-shock portion of the disturbance. As noted above, shock propagation takes place over a range of several milli-meters and several microseconds. To obtain significant measurements on such a scale, it would be necessary to make use of ultra-high-speed photo-graphy, perhaps in the form of an image-converter camera.

Lucite is an attractive material to use, not only because its trans-parency in portions of the visible spectrum permits shock photographs to be taken, but also because it can be shocked quite easily. Figure 7 shows the power-density rating of shock waves in Lucite. It should be noted that even as modest a figure as 10^9 watts/cm^2 corresponds to a shock strength that should be easily detectable.

Beam-Vapor Interaction

Material evaporated during the early portions of the laser pulse may tend to absorb the subsequent portions, resulting in a distortion of the pulse and in a reduction of the total energy delivered to the target. The distortion

effect is not serious, as mentioned above, but the simulation would certainly suffer if a major portion of the incident energy were intercepted short of the target surface. This problem has been pointed out by Yura.[42] It was not encountered by Ready[34] in his carbon-block experiments, where the plume was not ejected from the target until after the laser pulse was completed. Yura[42] also mentions some experiments in which no such effects were noted.

Some order-of-magnitude estimates given recently by Rothstein[43] suggest that the problem may not be serious. Rothstein estimated the plasma frequency of the evaporated material, and compared it with the frequency of the laser beam. An upper limit for the plasma frequency can be found by assuming that the vapor density is equal to that of the solid, and that each atom is singly ionized. The number density of electrons is then equal to the molar density of the solid. For a solid of density 10 gm/cm^3, and atomic weight 100, the molar density is $10^{-1} \text{ moles/cm}^3$, or $6 \times 10^{22} \text{ atoms/cm}^3$. If each of these is singly ionized, the plasma frequency is $1.38 \times 10^{16} \text{ rad/sec}$. Laser light of $7000\overset{\circ}{A}$ wavelength has a frequency of $2.7 \times 10^{15} \text{ rad/sec}$, which indicates that reflection would occur. The plasma frequency would become equal to the light frequency (indicating the beginning of transparency) if the atoms were only 10% ionized, or if the density fell by a factor of ten due to expansion of the vapor.

Estimates such as these indicate that the vapor quickly becomes transparent. It also indicates that proper selection of a layer of surface material could be used to improve the transparency.

A second possibility for minimizing the problem is indicated by Ready's observations.[34] The fact that a delay occurred between completion of the laser pulse and commencement of the vapor emission suggests that use of a carbon insert as an energy receptor may be effective.

On the whole, the indications are that the beam-vapor interaction will not be a serious problem, and that suitable composition of the layers near the surface offers a means for minimizing it.

V. CONCLUDING REMARKS

This report has examined the possibility of using a laser to simulate the effects produced by the impact of a high-speed particle. Advantages and limitations of the technique have been discussed; they indicate that its unique advantages warrant experimental verification.

It is well to bear in mind that the simulation contains some currently untested concepts, which must be thoroughly investigated before accurate quantitative measurements, bearing on the impact situation, can be made. For example, the dependence of the shock strength on various parameters of the laser pulse (spot size, duration, etc.) must be established. In addition, the scale of the experiment is on the same order as that of the meteoroid environment itself; such a small scale necessitates measurement techniques which require considerable care. The difficulties introduced by this aspect of the problem can be expected to diminish in importance as more powerful laser systems are developed.

The feature that renders the simulation attractive is its prospect of providing a relatively simple and economical means of testing in a regime that is at present beyond the reach of conventional techniques. In view of these comments, it appears that simulation by a laser affords a useful parallel approach.

ACKNOWLEDGMENT

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See also Figure 3, page 3 of the same author's Introduction to the review: Von Karman Gas Dynamics Facility, ARO, Inc. , Technical Developments (1964).

TABLE II

Shock-Wave Properties of Selected Materials

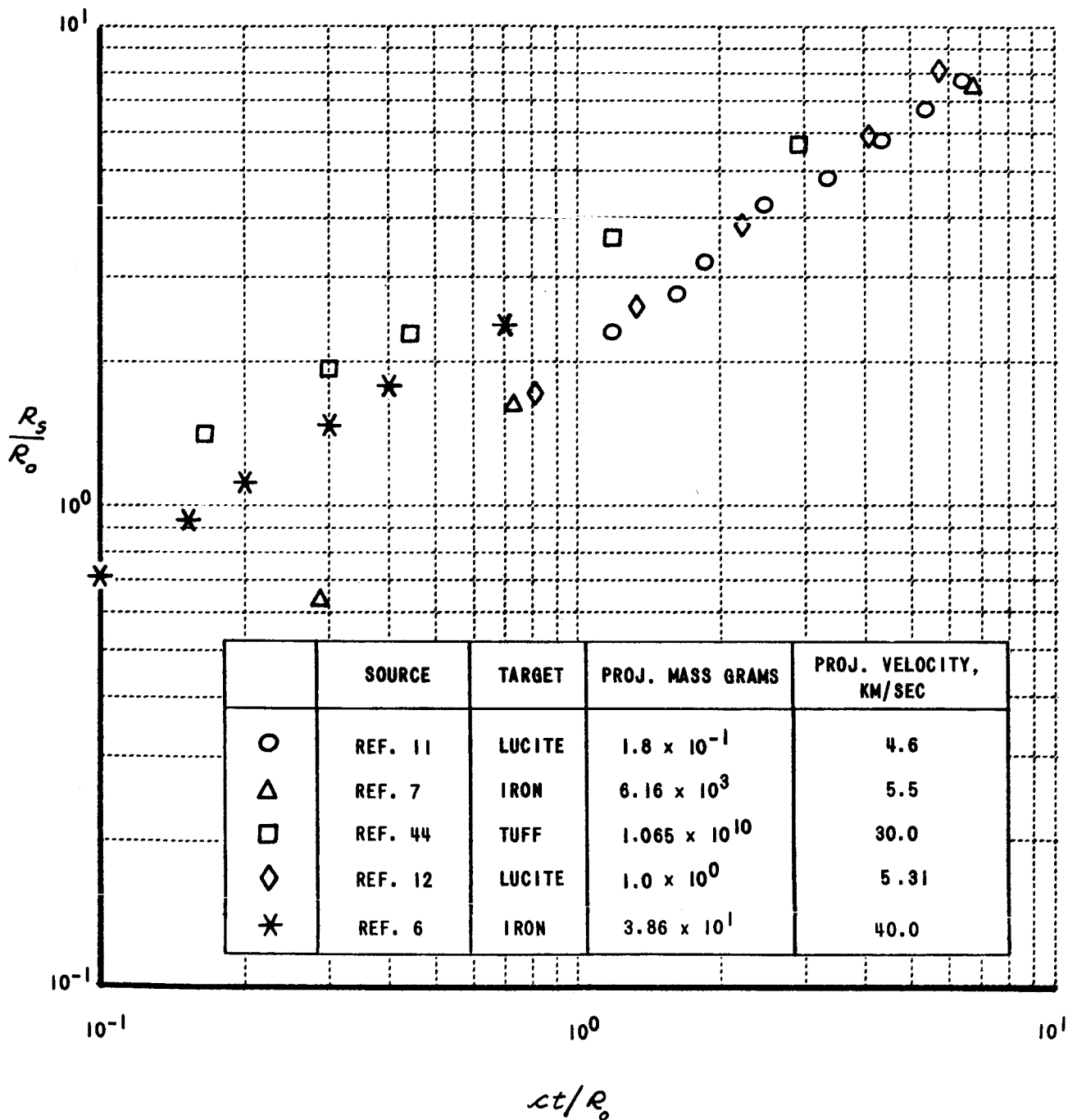| Material	ρ_0, gm/cm^3	c, km/sec	S	$\rho_0 c^3$, Watts/cm^2
Aluminum	2.7	5.85	1.11	5.40 x 10^{10}
Beryllium	1.82	7.98	1.09	9.23 x 10^{10}
Copper	8.90	3.97	1.48	5.58 x 10^{10}
Iron	7.87	4.00	1.59	5.03 x 10^{10}
Lead	11.34	2.07	1.52	1.001 x 10^{10}
Lucite	1.18	2.59	1.51	0.205 x 10^{10}
Fused Quartz	2.20	1.30	1.56	0.0484 x 10^{10}
Tungsten	19.17	4.00	1.27	12.28 x 10^{10}

Figure 1 CORRELATION OF SHOCK-WAVE TRAJECTORIES

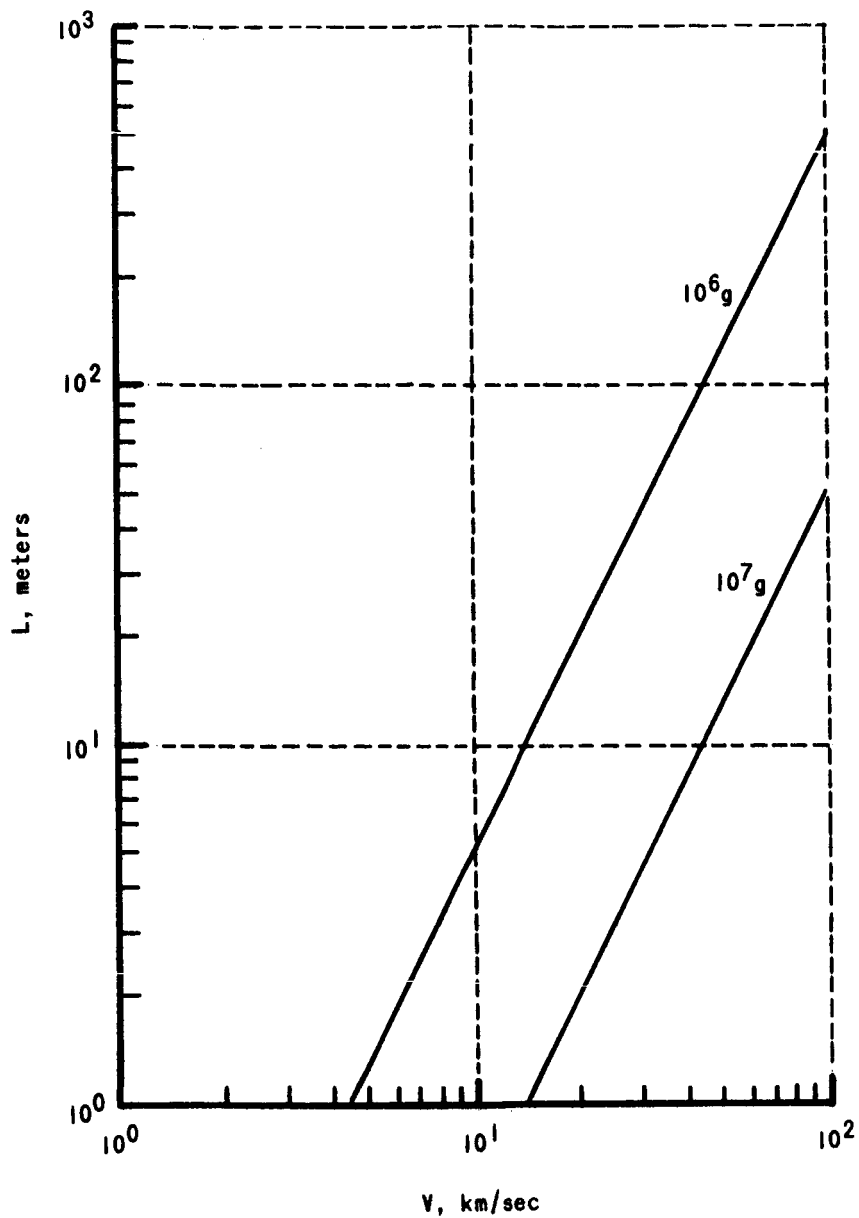$$R_o \equiv \left(\frac{E}{2\pi \rho_o c^2} \right)^{1/3}$$

The plot axes are $\frac{R_s}{R_o}$ (vertical) and $\mathscr{c}t/R_o$ (horizontal).

	SOURCE	TARGET	PROJ. MASS GRAMS	PROJ. VELOCITY, KM/SEC
O	REF. 11	LUCITE	1.8×10^{-1}	4.6
△	REF. 7	IRON	6.16×10^3	5.5
□	REF. 44	TUFF	1.065×10^{10}	30.0
◇	REF. 12	LUCITE	1.0×10^0	5.31
✳	REF. 6	IRON	3.86×10^1	40.0

Figure 2   LENGTH OF LAUNCH TUBE REQUIRED TO PRODUCE A GIVEN
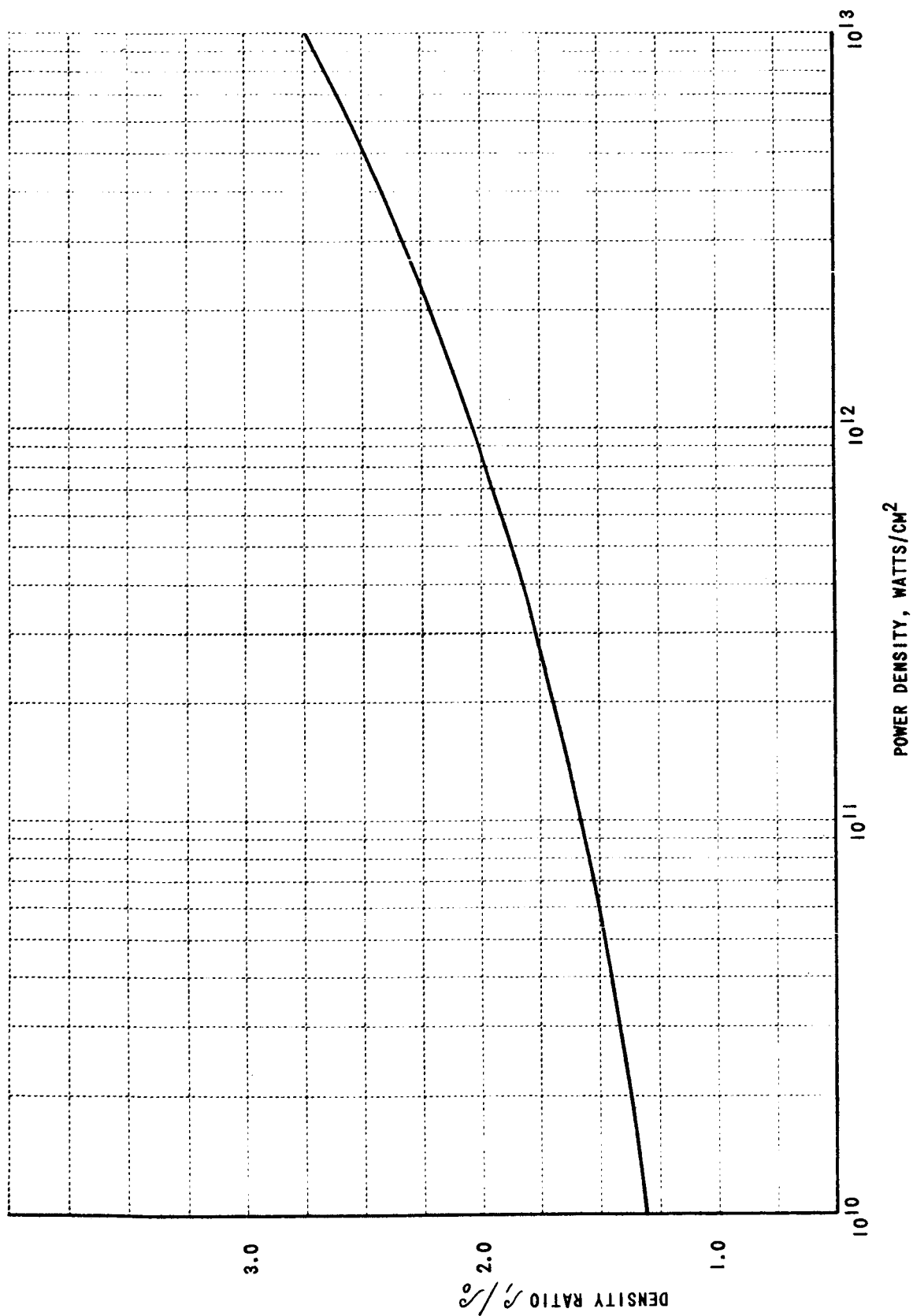MUZZLE VELOCITY AT CONSTANT ACCELERATION

Figure 3 POWER-DENSITY RATING OF SHOCK WAVES IN IRON
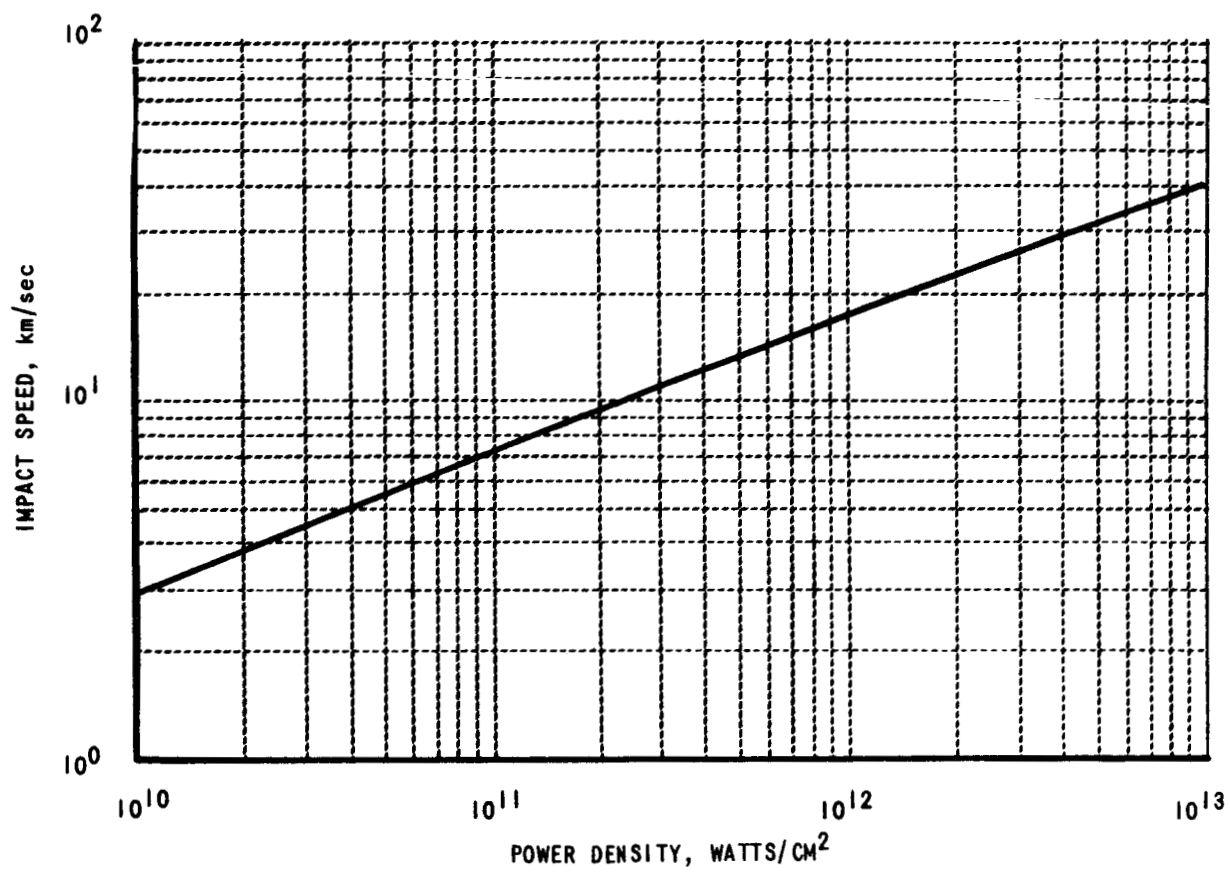
Figure 4 POWER-DENSITY RATING OF SHOCK WAVES DRIVEN
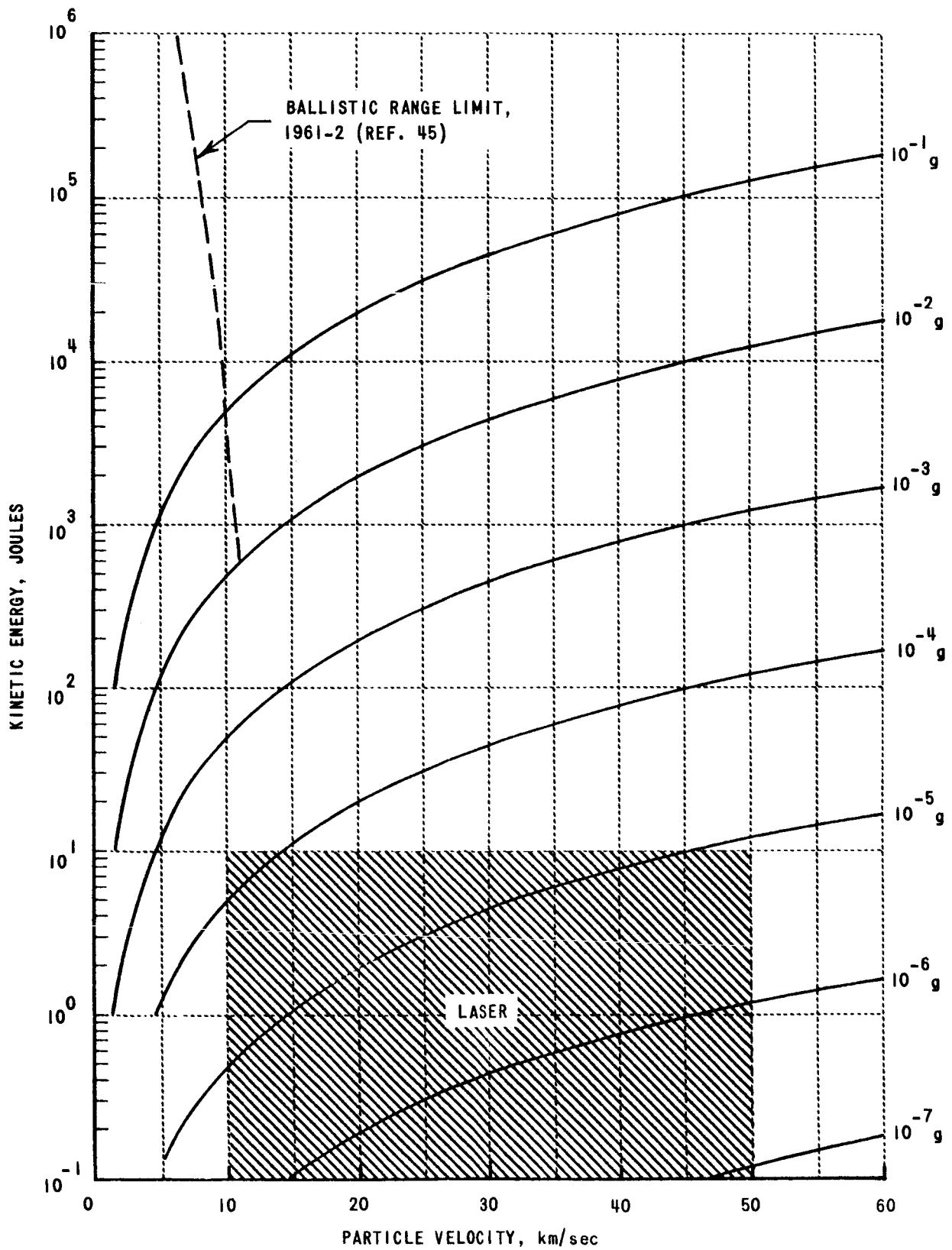INTO IRON TARGETS BY IRON PROJECTILES

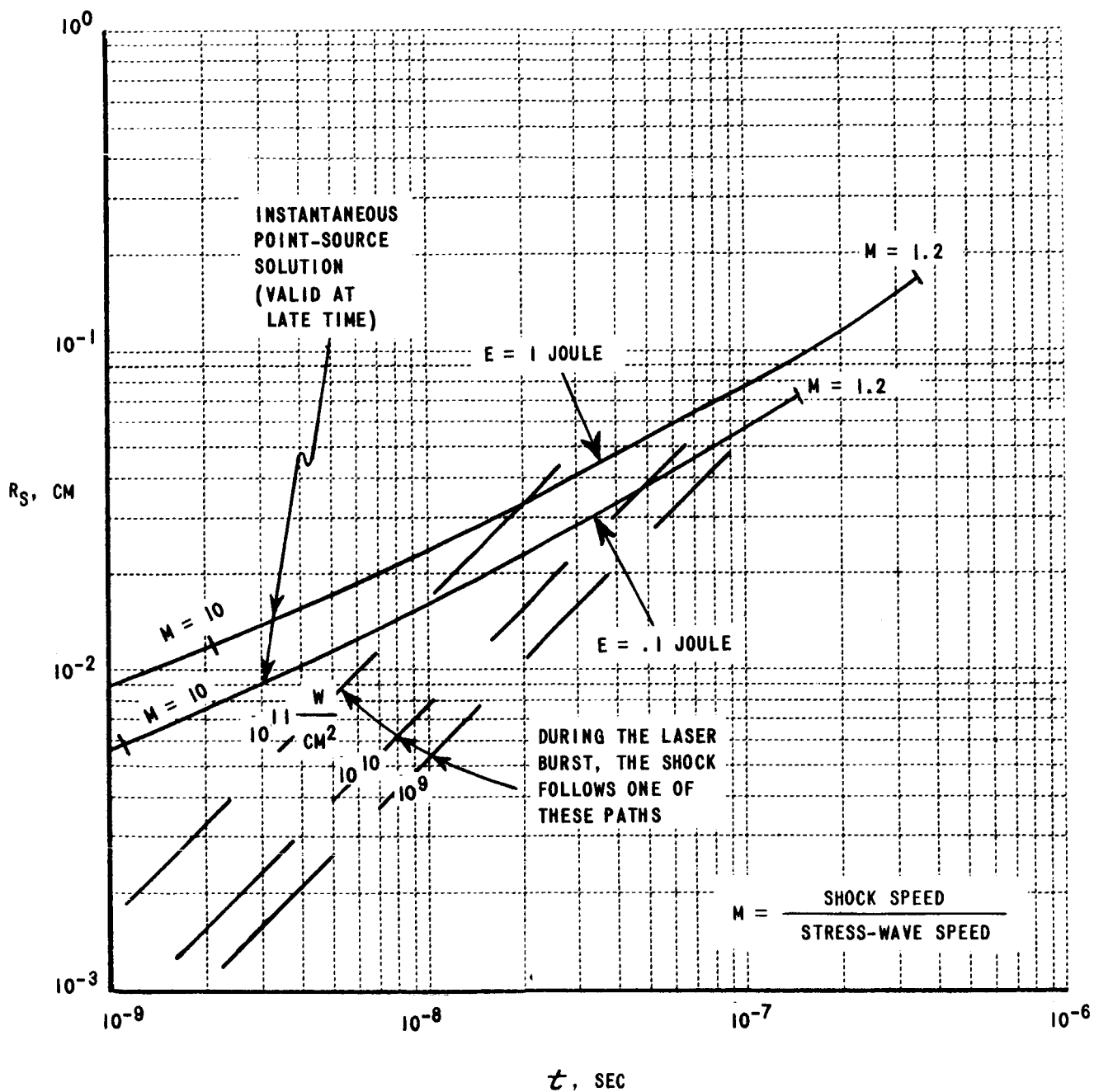Figure 5   ENERGY RANGE OF METEROID ENVIRONMENT
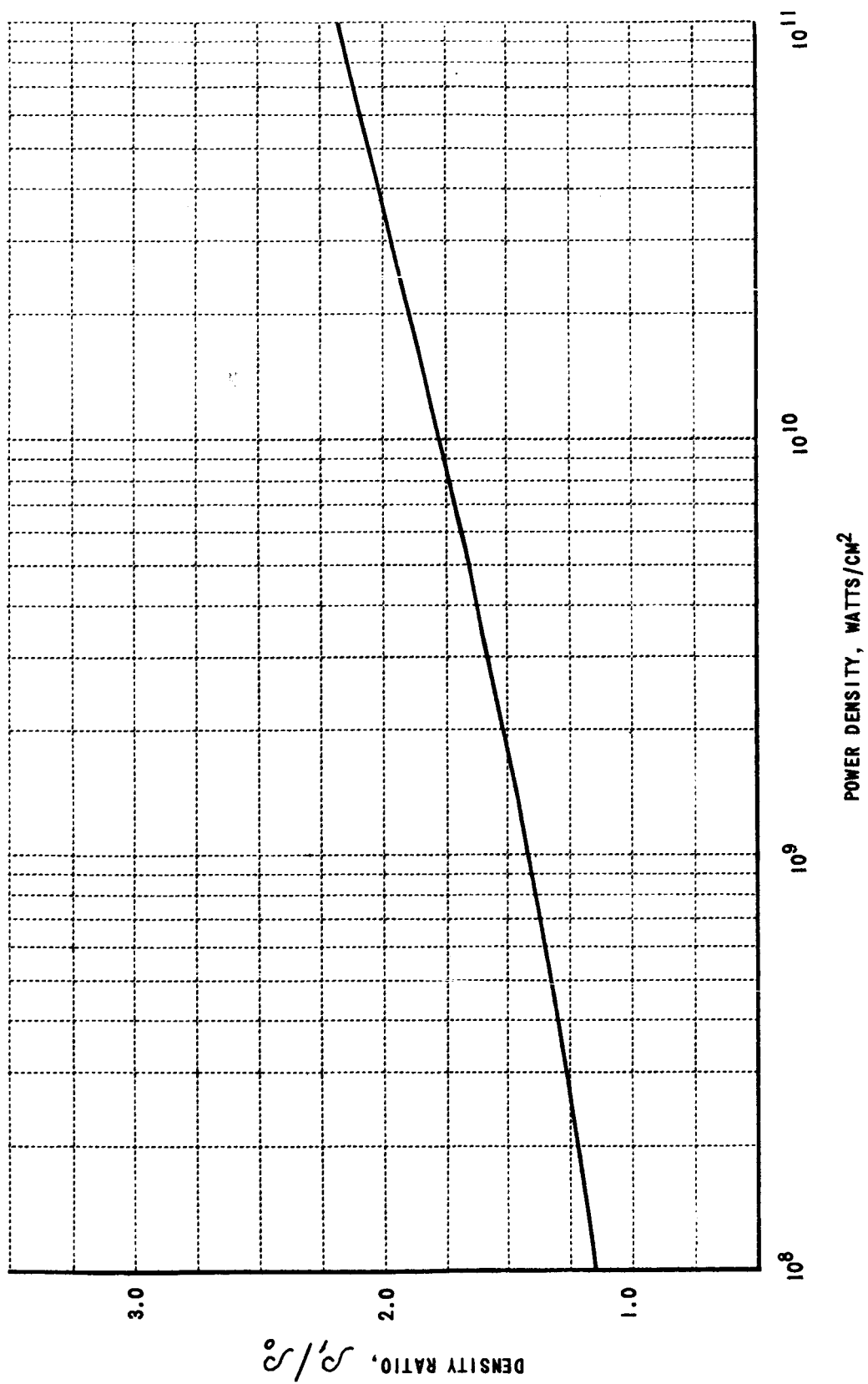
Figure 6 LASER-GENERATED SHOCK PROPAGATION IN LUCITE

Figure 7 POWER-DENSITY RATING OF SHOCK WAVES IN LUCITE

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